Keck Science Phase 2

Michael Shao

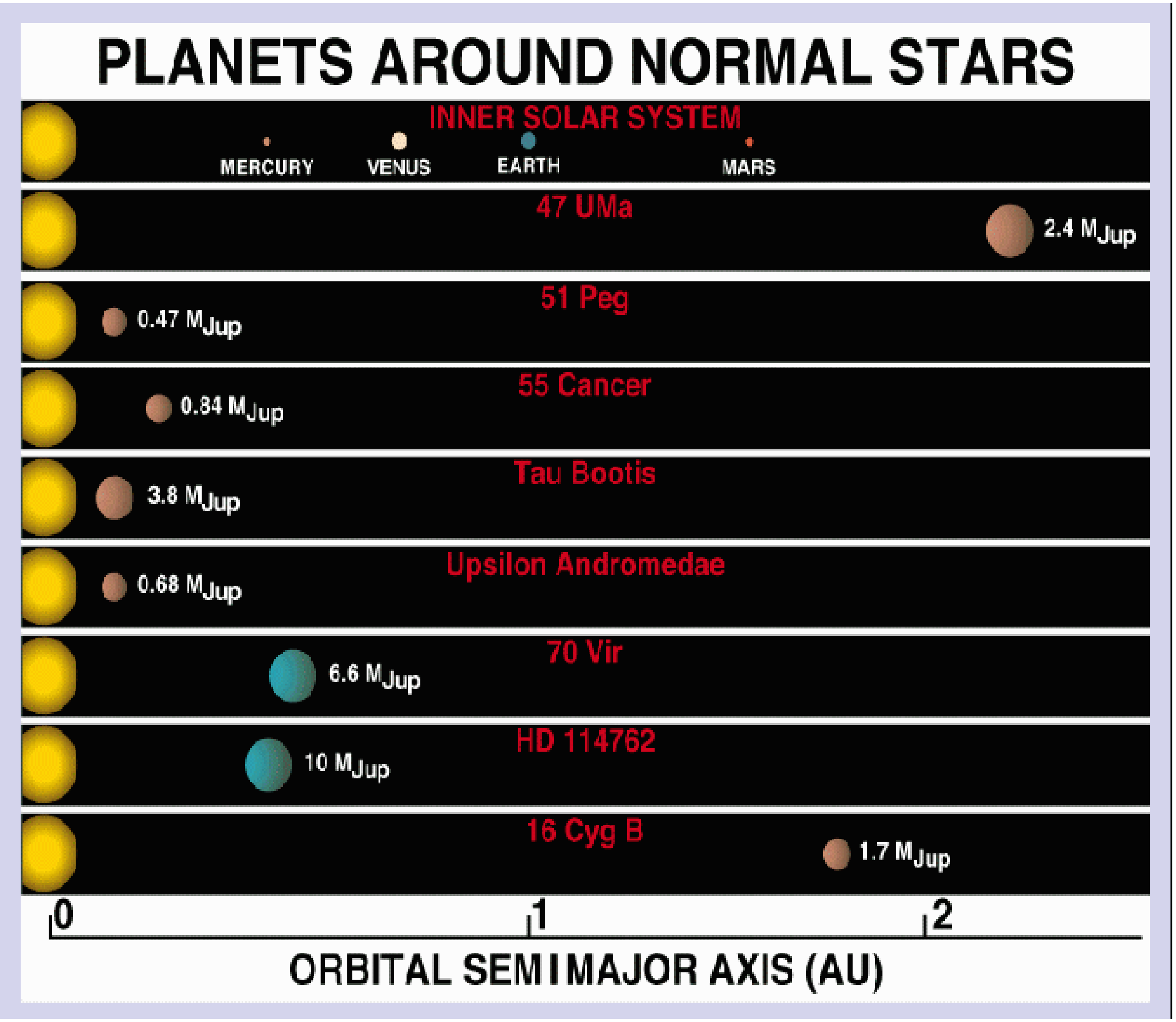
Phase 2 Facilities

- Phase 2 is 2 element interferometry between the two 10m Kecks (and possibly between a 10m and a ~80cm test telescope)
  - Dual star observations (2 um)
    - phase referencing for faint object interferometry
    - astrometry demonstration (excellent seeing)
  - Nulling interferometry (10um)
  - Natural guide star AO for Keck 1

Phase 2 Science

- Hot Jupiters
  - Direct detection of Hot Jupiters
  - Spectroscopy of planetary atmospheres
- Exozodi characterization
  - The reason why this problem is important for NASA
  - Interferometric chopping, background limited detection at 1e-7 of the background
- (Technology) Demonstrate differential astrometry under excellent seeing conditions

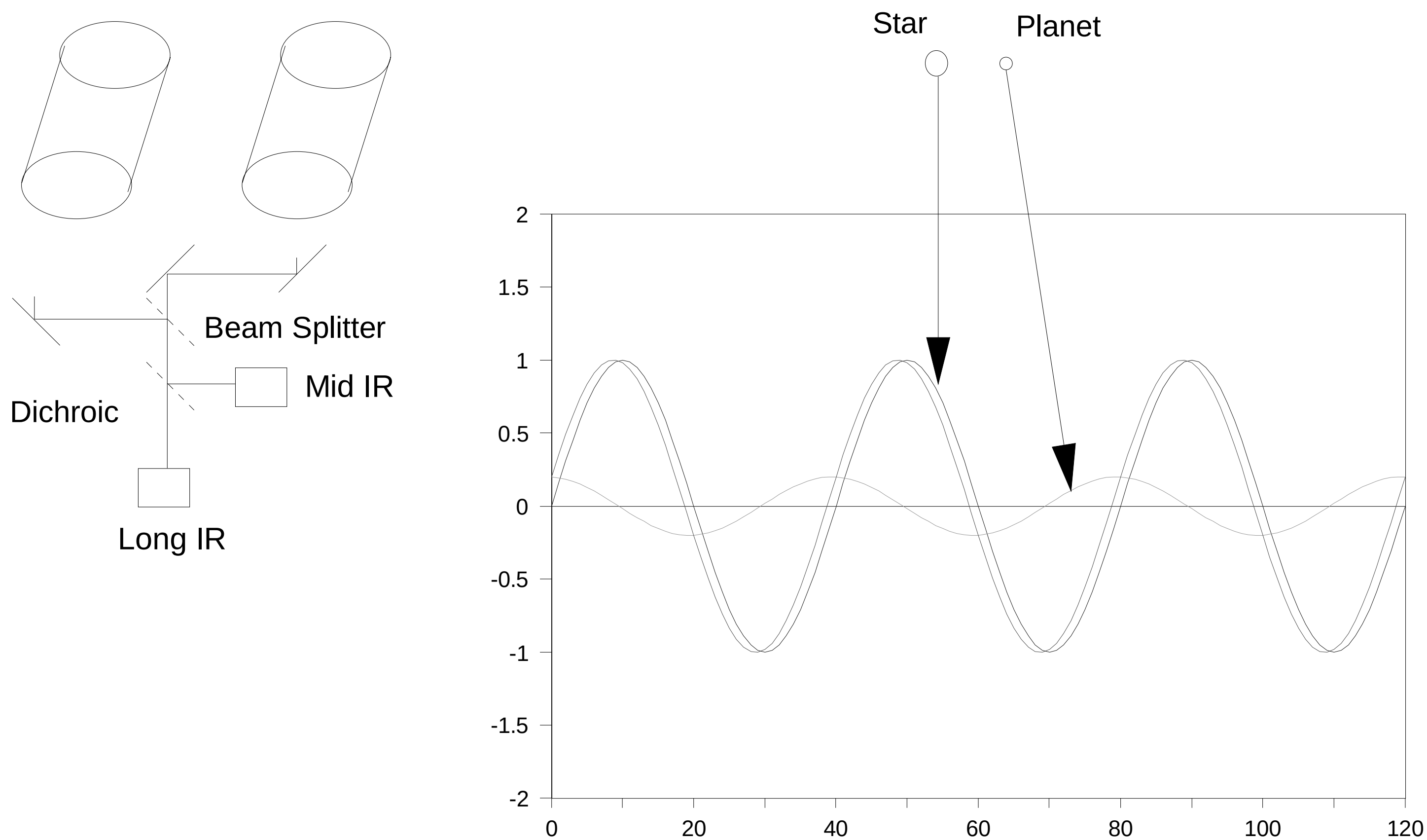
Hot Jupiters



From G. Marcy's Web page.

Masses are Msin(i)

Direct Planet Detection From the Ground

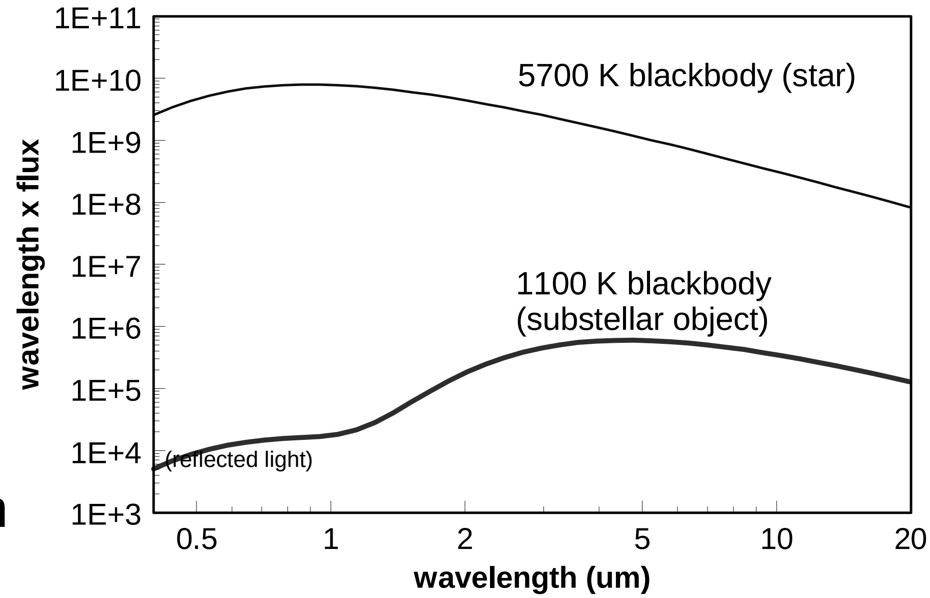


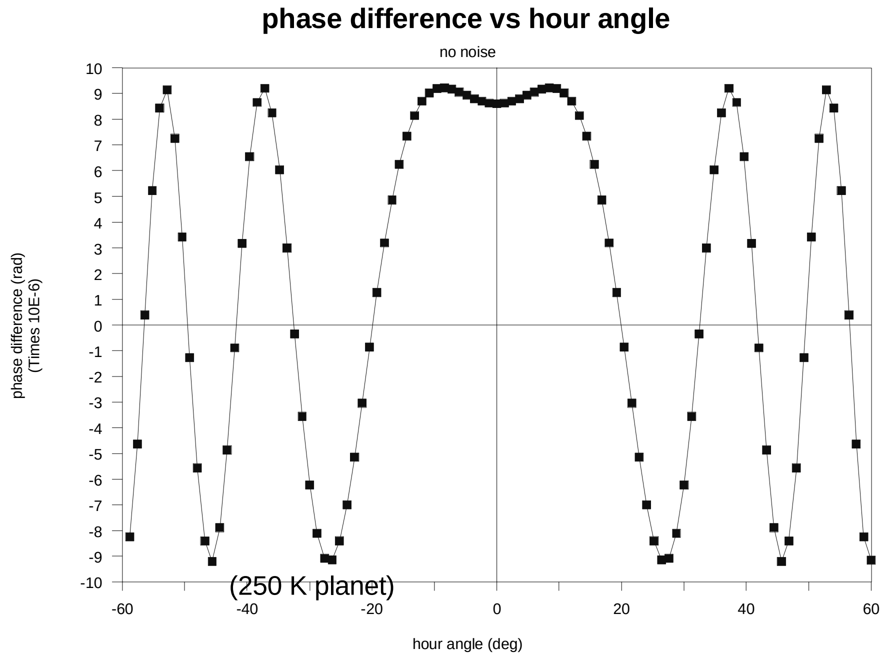
Phase Difference Interferometry for Planet Detection

viewgraph made in 1990

Direct Detection of Hot Jupiters

- Problem is not SNR - need to control systematic errors
- Use two-color phase referencing
  - Use object observed at a short wavelength as phase reference
    - Center of light will be close to star
  - Observe object at a longer wavelength for science measurement
    - Center of light will be displaced toward planet
  - Phase difference is observable
    - Very insensitive to systematics
- Observations of GL229B showed that significant changes in the flux ratio may be present just within the 1.6 and 2.2 um bands.





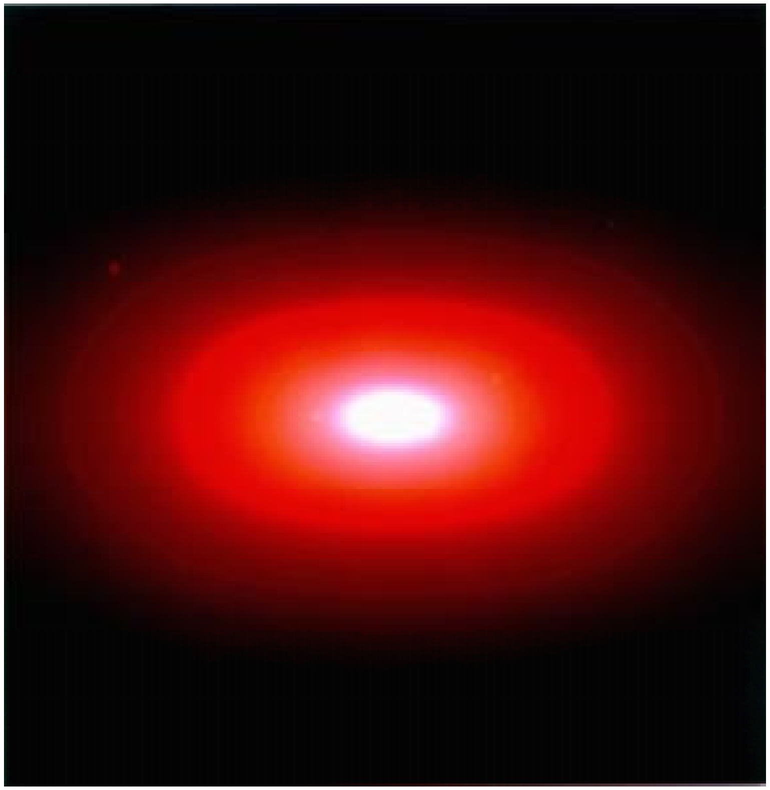
SNR for Hot Jupiters

	1300K (51 Peg)		650K	
Lambda	Contrast	SNR (0.2bw)	Contrast	SNR
1.2	7e-6	0.85	7.4e-10	8e-5
1.6	3.9e-5	4.1	4e-8	4e-3
2.2	1.5e-4	12.6	1e-6	0.08
3.5	4.9e-4	29.6	2e-5	1.2
5	8.5e-4	36.4	8.3e-5	3.6
10	1.5e-3	6.6	3.4e-4	1.6

Contrast is planet/star flux ratio

SNR is signal/noise in 1 second integration with 2 Kecks

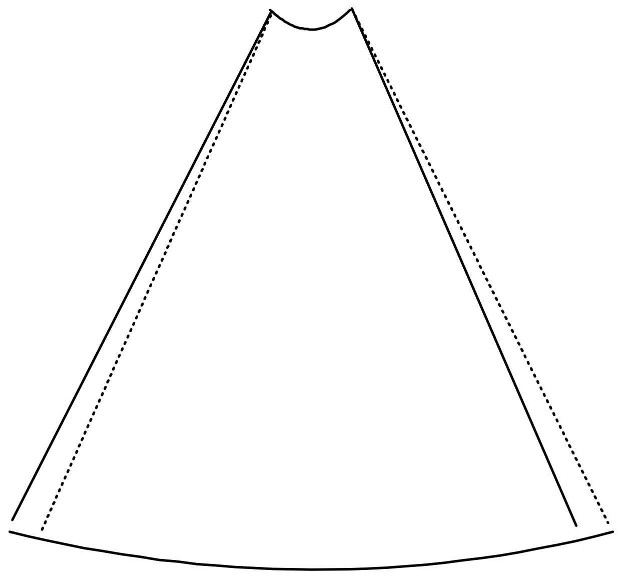
Exo-Zodi



- NASA is very interested in finding Earth like planets around nearby stars (described later)
- There is one unavoidable source of astrophysical "noise", the disk of dust around the target star.
- For our own solar system, the dust in the inner solar system will emit more 10um radiation than an Earth (~50).
- Interferometer is the only ground based technique that can measure the dust emission ~1 AU from the star.

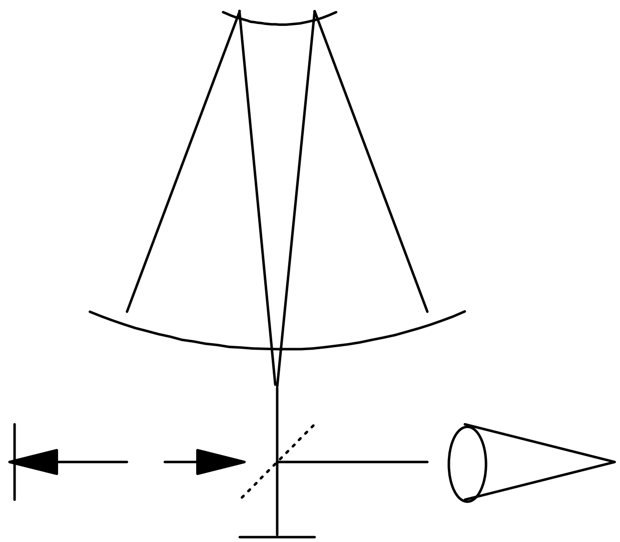
Faint Objects in High Background

- IR (10um) astronomy has to live with a huge background, compared to the strength of the sources.
- The standard technique used to subtract the background is sky/sky chopping
- Ideally we "chop" the whole telescope at 10's hz. In practice, a chopping secondary is used.
- Assuming a 10 urad chop, the 10m footprint on the primary moves 170 um . ~2e-5 change.
  - Background stability to 1e-7 implies the temp gradient of the primary is stable to ~0.25 degC.
  - Assuming the detector doesn't see past the edge of the primary



Interferometric Modulation

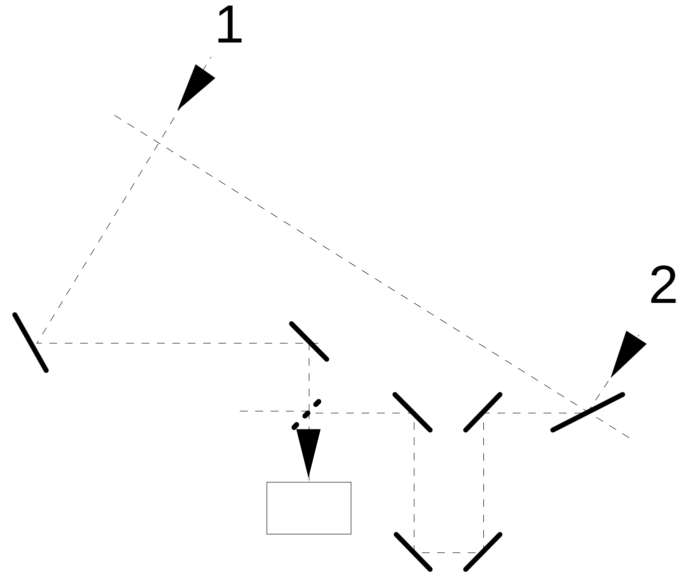
- Sky-sky chopping, modulates the stellar signal, but also slightly modulates the background
- Is it possible for "interferometric" chopping to just modulate the star?
- Take two cases, a Fourier spectrometer, and a stellar interferometer.
  - A Fourier spectrometer behind the telescope, measures the spectrum of the star+optics
  - Path modulation in a FTS modulates both the background and the star
  - Background is modulated because at zero path difference, both the background and star are coherent.



Example where interferometric modulation also modulates the background

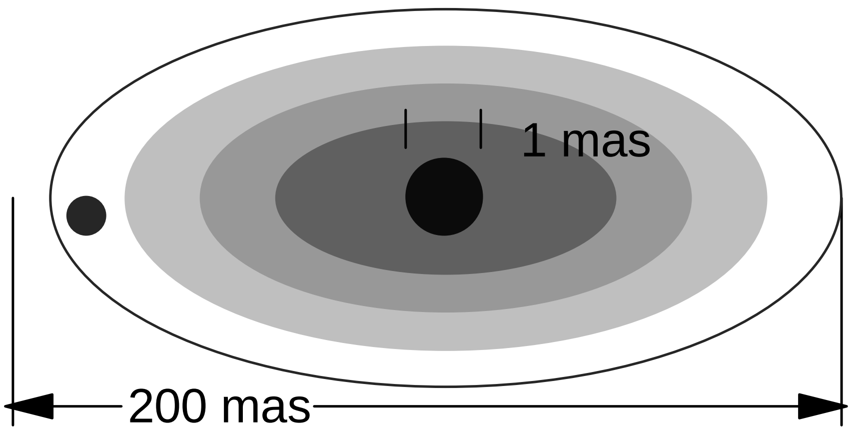
Interferometric Modulation

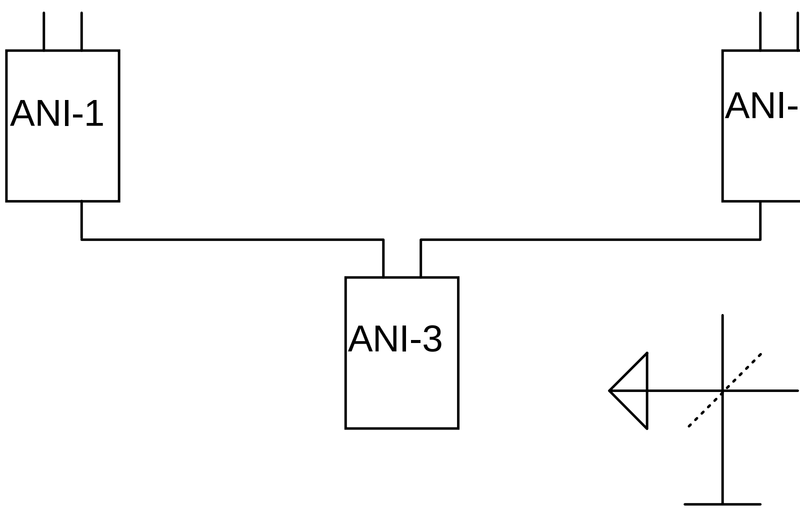
- For a spatially unresolved source, interferometric modulation is done by changing the optical path. (Khz)
- The coherent stellar signal is modulated.
- The background is constant.
  - The background is incoherent
    - The background IR emission from Keck 1, doesn't interfer with the IR emission from Keck 2
    - The IR sky emission in beam 1 comes from different atoms in the atmosphere than from beam 2.
  - The A*Ω the detector sees is constant (during path modulation)



Single Det. Path Modulation

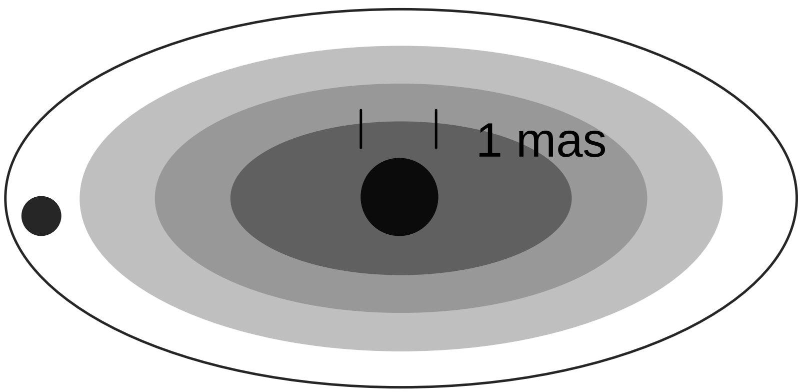
Exo-Zodi Detection (Keck)





- Background is only 1 problem the other is the star
- The basic technique uses nulling interferometry
  - ANI-1 (within a single 10m aperture nulls both dust and Star)
  - ANI-3 (between Kecks) nulls just the Star
- ANI-1 (B+Z+S, B+ε(Z+S))
- ANI-3
  - B+Z+S, B+Z-εS
  - B

Zodi Detection Details



λ/10m ~ 200 mas

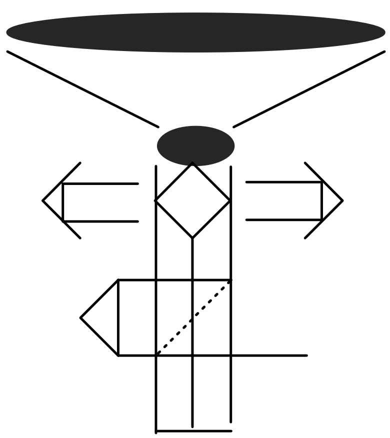
λ/85m ~ 24 mas

B+S+Z	0	I
B+ε*(S+Z)	π	II

B background

S star

Z exo-zodi



I	0	
B+S+Z		B+εS+Z
II	π (for ANI-1,2)	
B+ε*(S+Z)		B+ε(S+Z)

B 2e10

S 6e 8

Z 2e 4

Exo-zodiacal SNR

- Assumptions
  - 10um
  - 0.3 $d\lambda/\lambda$
  - Star @ 10pc
  - $\varepsilon = 0.5$
  - QE 0.75 (for background)
  - Total system eff 0.1
  - $A\Omega = 1\ \lambda^2$ (single mode filter)
- Assumed stability (10 msec)
  - IR emission 4e-5
    - 2 mK/10msec thermal drift random (12 K/min)
    - 1.2K/min (1sec)
  - Null stability 2% (98+/-2%)

what	*photons/sec*
Star	1.5e8
Background	7.0e10
Exozodi (10 x solar system)	1.3e5
SNR in 1 hr	15~30

Keck Science Phase 3

Michael Shao

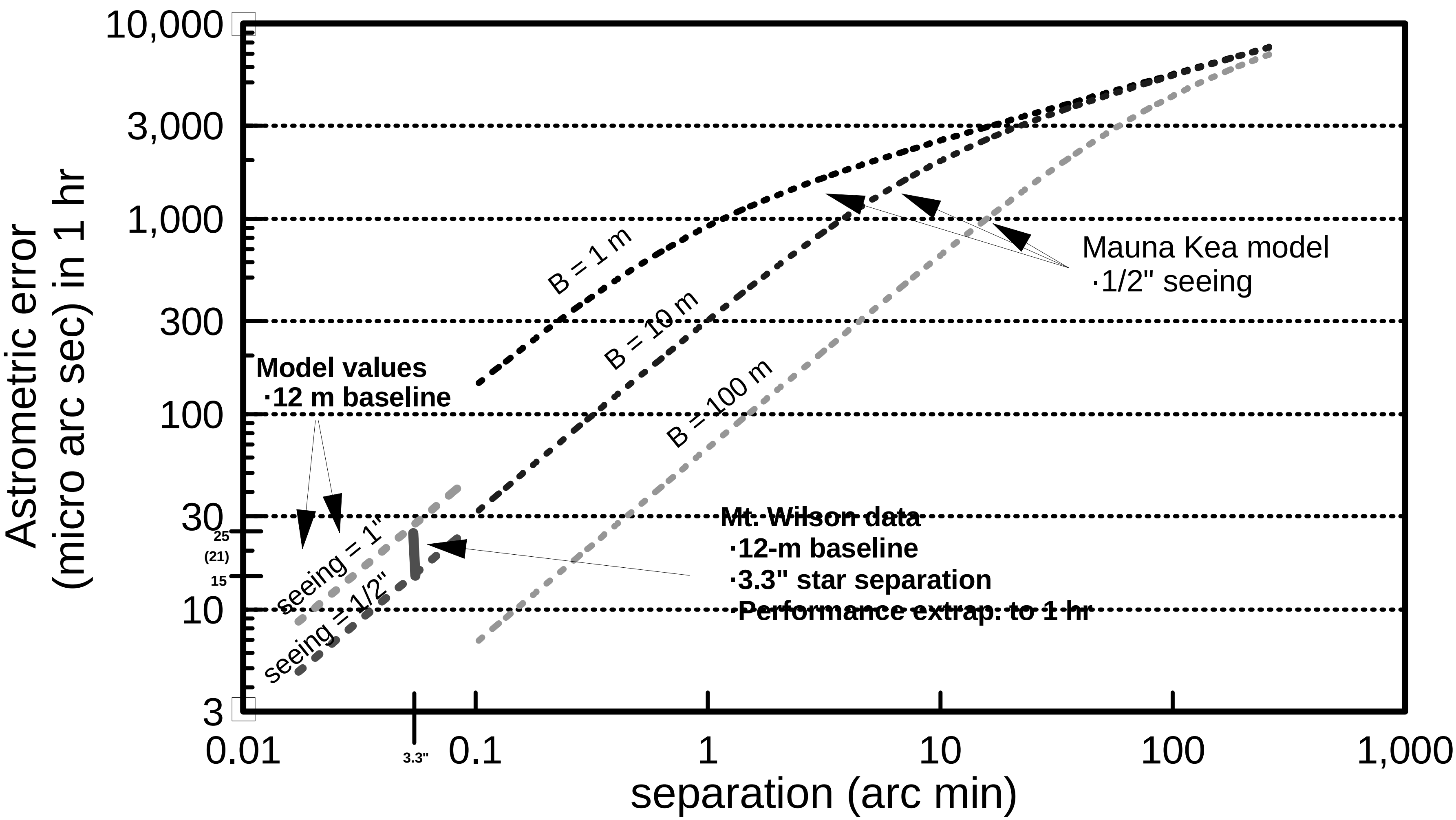
Phase 3 Facilities

- Phase 3 is the ~ final facility
  - ~4 1.5~2.0 meter "outrigger" telescopes
    - With dual star/phase ref capability
  - 6 way beam combiner @ 2um
  - 6 way combiner @ 5, 10um ??
  - Laser guide star AO for Keck 1
- Note that to use the analogy of an interferometer as a telescope, the back end beam combiner is analogous to a telescope's science instruments.
  - As part of the operation of the Keck interferometer, new instruments (beam combiners) should be developed every few year(s) after the initial instruments become operational.

Phase 3 Science

- Astrometric search for planets around many 100's of nearby stars down to Uranus mass.
  - Use outrigger telescopes for long term survey
    - Two ~ orthogonal baselines ~100m long
    - ~2m outriggers should reach down to ~20 mag for astrometric reference, reference available for > 90 of nearby stars.
- Imaging with 6 element array.
  - Reasonable uv-plane coverage with 6 elements if the outriggers are movable
  - With 4 outriggers, 9 of 15 baseline have at least 1 10m
  - 10m + 2m = two 4.4m's. (for background or detect noise limited IR operation)

The Theoretical Limits to Ground Based Astrometry



Overview of Capabilities

- Maximum baseline: ~100 m
- Sensitivity

wavelength	Unphased	Phased	Cophased
2.2 um	12.3 mag(K)	15.8 mag(K)	21.8 mag(K)
5 um	8.1 m(M)	9.7 m(M)	15.0 m(M)
10 um	6.3 m(N)	6.7 m(N)	11.6 m(N)

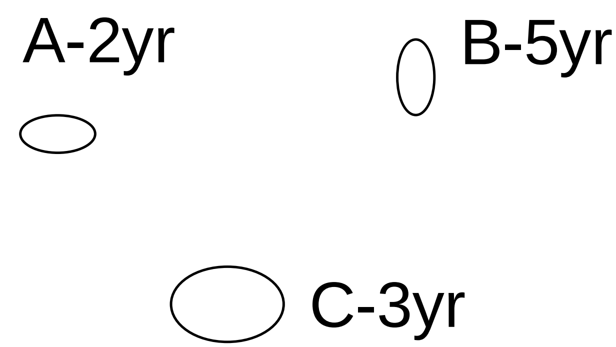
Unphased: No AO, fast readout (atmospheric rates)

Phased: AO to provide phased 10-m aperture, fast readout

Cophased: AO + phase referencing to provide (assumed) 500-s coherent integration

Astrometric Search

- Astrometric search looks for the wobble of one star relative to a nearby star.
- With just two stars it’s not possible to determine which star has a companion.
- With two reference stars, and the assumption that the companion orbits are not the same, it is possible to identify which star has what companion
- A differential astrometric search has to have 2 or more reference stars.



A-C will show 2,3 yr periods
B-C will show 3,5 yr periods
A-B will show 2,5 yr periods

Best Case Astrometric Performance

- Assume
  - Keck Interferometer with 2-m telescopes, 100 m baseline
  - 1/2-arc sec atmospheric model with a 40-m outer scale
  - 90% probability of 2 reference stars in field
  - Use mean star densities from Allen; K mag estimated as V - 3 assuming K5 spectral type
  - Reference star measurements are background/sky limited

radius for 90% prob. of two references	cut-off K-mag	average K-mag	atmospheric error in 1 hr	photon noise in 1 hr	total noise, 1 reference star, 1 hr	**total noise, both reference stars, 1 hr**
20 arc sec	17.5 magK	16.8 magK	8 uas	6 uas	10.5 uas	**7.4 uas**

Phase Ref Interferometry

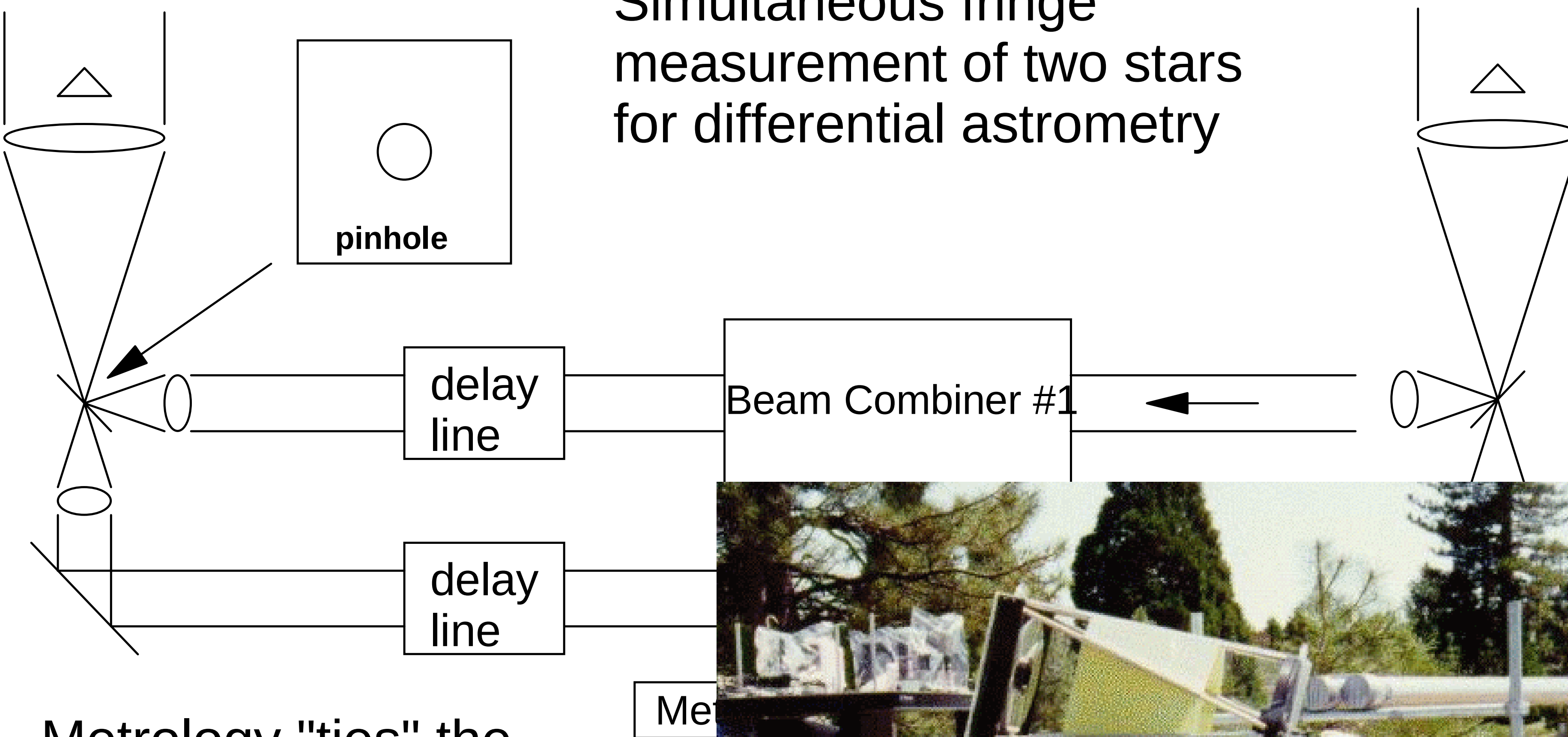
- Conventional ground based interferometry is limited by the turbulent atmosphere, r0 limits the sized of the telescope and t0 limits the coherent integration time.
- The object must be bright enough to produce a SNR~4 using moderate sized telescopes (r0 diameter) and short integration times.

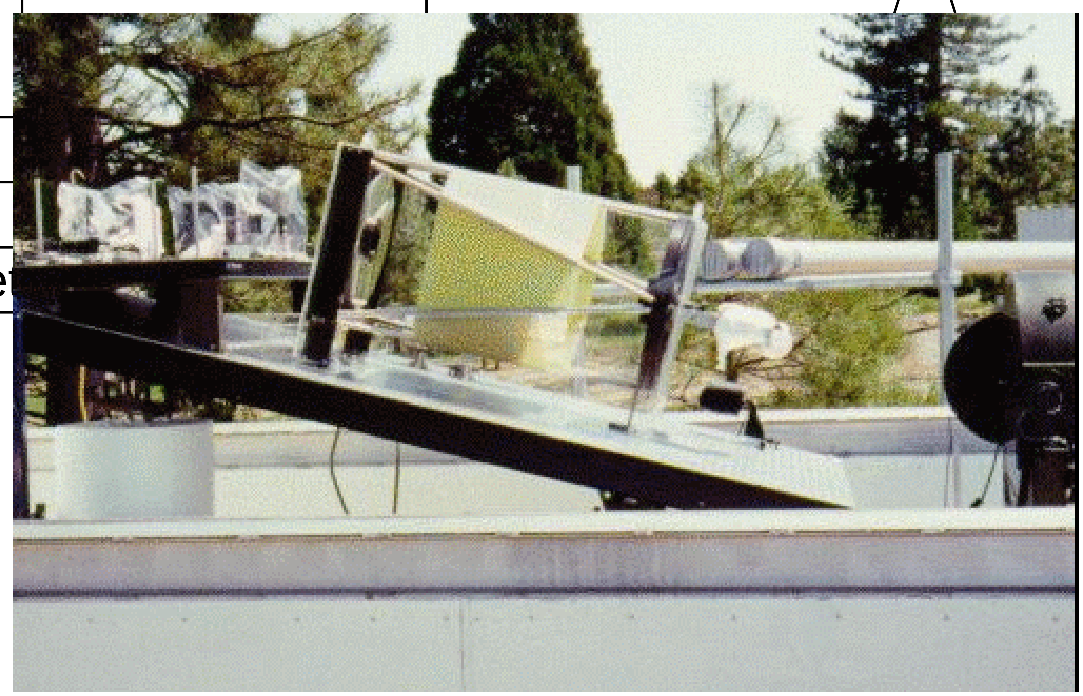
Instrument	r0	t0	t0*r0^2
Convention	50 cm	20msec	50 cm^2*sec
PTI	50 cm	200 sec	500,000 cm^2*sec

Palomar Testbed Interferometer

Dual Object Interferometry

Simultaneous fringe measurement of two stars for differential astrometry



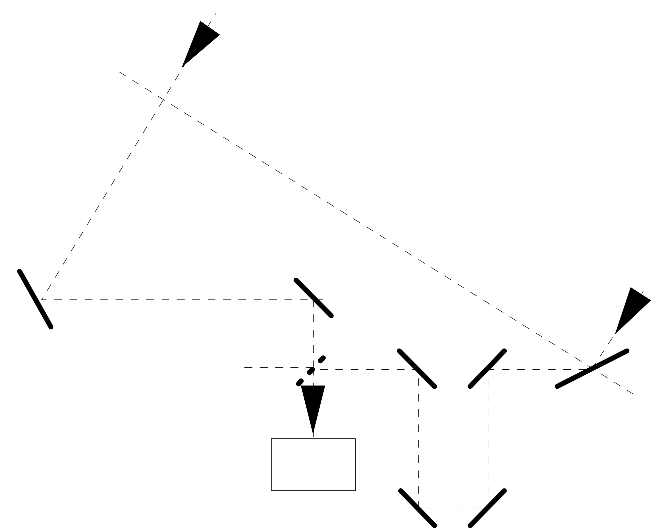


Metrology "ties" the two beam combiners together (~10 nm)

Optical Interferometry

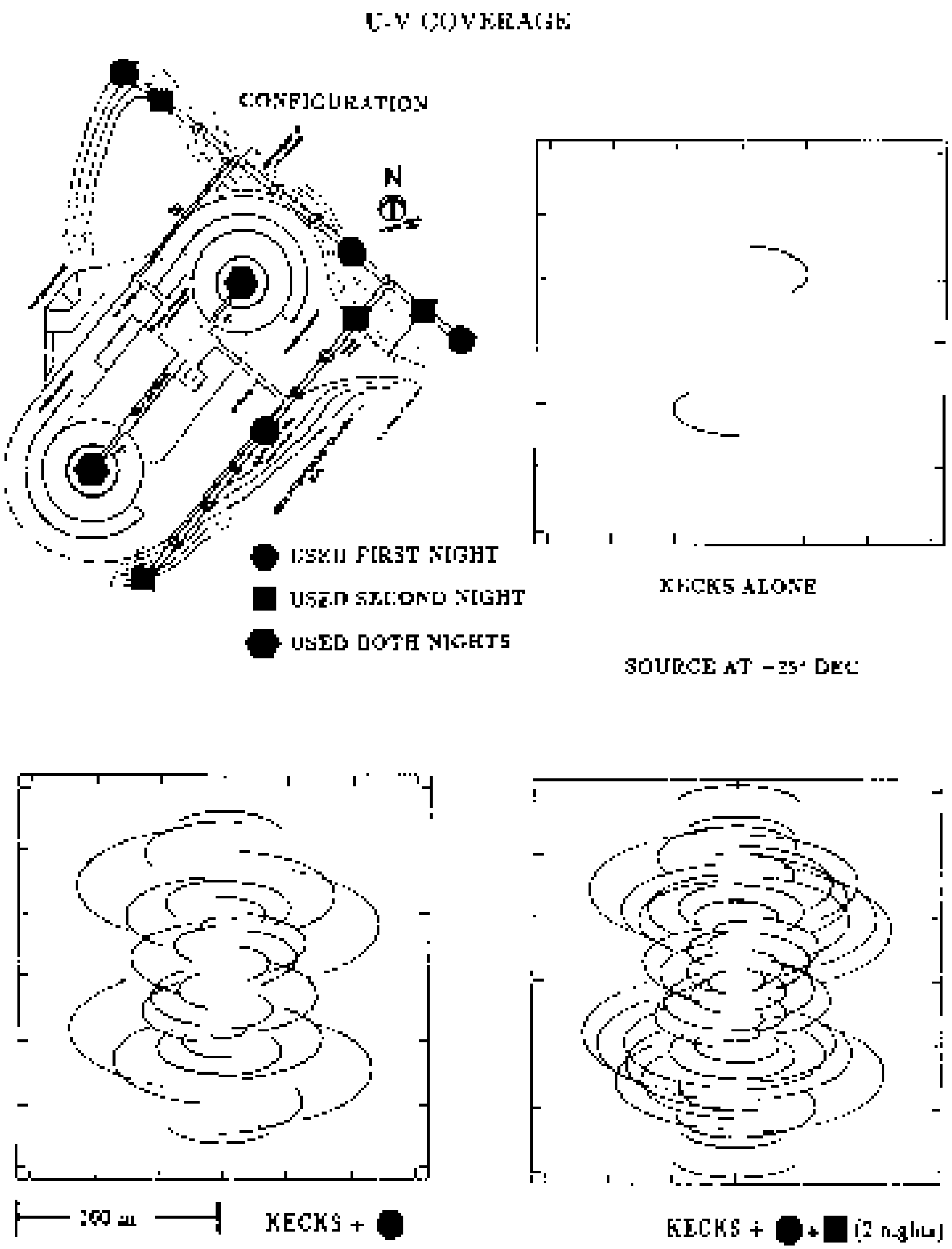
- Interferometry is the coherent combination of light from multiple telescopes to obtain information that is possible only from very large telescopes.
- The potential advantages of interferometry have been known for many decades.
- Interferometry at JPL started at a similar meeting.

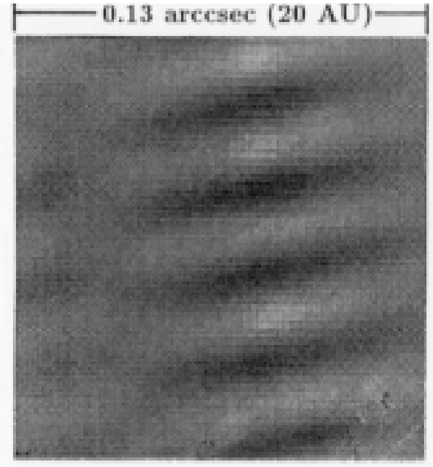
Pupil Plane Interferometer



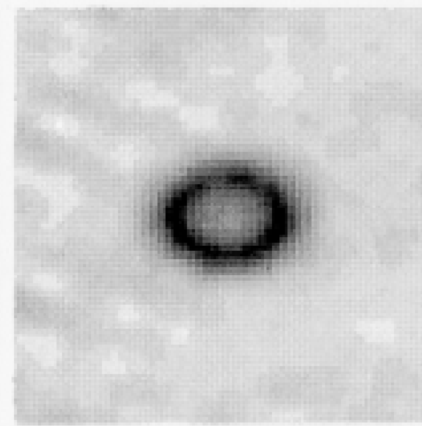
Single Det. Path Modulation

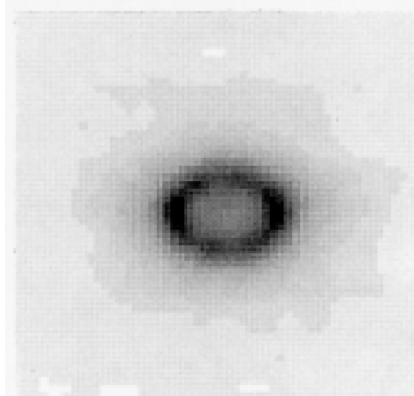
Imaging Performance





KECKS ALONE


WITH OUTRIGS, 1 NIGHT


WITH OUTRIGS, 2 NIGHTS